Application of Genetic Algorithm to Optimal Design of Central Air-Conditioning Water System

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Abstract: The optimal design of air-conditioning water system is an optimization problem of functions that depend on a series of nonlinear discrete multi-variables． Many traditional methods are not satisfactory when applied in this field. However, genetic algorithm (GA) has special advantages in tackling this problem based on its inherent characteristics． Genetic algorithm (GA) is adopted and applied in the optimal design of air-conditioning water system in this study. A mathematical model and constrained conditions are put forward. This paper gives an overall introduction of basic principles of GA and analyzes the characteristics of water system, the pipe code technology, the evaluation function, crossover operator and mutation operator of GA. An optimal design program of central air-conditioning water system has been made using GA. In order to verify the effectiveness of the program, a practical project is analyzed. A comparison of GA and the traditional velocity method shows that more economical solution has been achieved by using GA. It is concluded that GA provides better optimal solutions for air-conditioning water system design.

Key words: central air-conditioning water system; optimal design; mathematical method; genetic algorithm(GA).

1. INTRODUCTION

Water system is an important part of central air-conditioning system. Water system design will play a key role in reducing initial investment and operating cost of water system. It is necessary to apply the optimal methods in pipe segments arranging and pipe sizing providing that water pressure and quantity meet occupants’ demands.

In present central air-conditioning water system design, the methods of velocity or recommended specific frictional heat loss are used widely in China. The two methods can only accomplish local optimism, the overall investment cannot reach the lowest level. As known, the recommended velocities and the recommended specific frictional heat loss vary with the different pipe sizes and water flow. In addition, the differential method is used to calculate recommended specific frictional heat loss, whereas, differential method requires objective functions to be consistent and differential. Using recommended frictional heat loss, the obtained pipe sizes are consistent, however, the standard pipe sizes are discrete variable. Thus, when the standard pipe sizes are selected through the calculating values, the final pipe sizes applied in practical projects deviate from the optimal ones to some extent.

Considering that the mathematical model of the pipe optimization is non-linear multi-target functions, and pipe sizes are discrete variable, it is difficult to solve the model. Applying the traditional methods (linear programming and non-linear programming), the mathematical model needs to be simplified. Therefore, the obtained solutions are only approximate to the optimal values. With the rapid development of computer technology and optimization algorithm, heuristic optimization algorithms are widely used in engineering optimal design.

In this paper, genetic algorithm is applied in the optimal design of air-conditioning water system. The principle of GA is illustrated, the pipe code technology, the evaluation function, crossover and mutation operator is analyzed. A practical application demonstrated that the optimal design using genetic algorithms could save investment and operating cost by comparison with traditional methods. Satisfying solution is achieved.

2. THE PRINCIPLE OF GENETIC ALGORITHM AND CHARACTERIC

The philosophy of genetic algorithms (GA) derived from the biological law. GA is a kind of parallel algorithm by simulating the biological genetic heredity and evolution. In the method, a mathematic model is built and the decision-making variable named gene is coded. A few genes form an individual named chromosome. A group of individuals composes of a population. The fitness value of every individual is calculated by the optimal objective function, and it decides the surviving probability of every individual. When the iteration computation begins, an initial population is generated. The surviving probability of every individual is determined by the fitness value. By means of selection, crossover and mutation operator, the fine performance population is remained and inherited[1,2,3].

Genetic algorithms applicated in pipe optimal design have the advantages as follows.

(1)Genetic algorithms only need fitness value and don't depend on the question. It can adapt to the requirement of pipe network optimal design and get a optimal solution.

(2) GA search method complies with random transformation rule and use heuristic search under the constrained conditions. Search extension and directivity is considered and search efficiency is high.

(3) When objective function change with system running cases ,some optimal algorithms lying upon objective function can not fit to the change. However, GA don't depend on objective functions, It can adapt to new conditions when some small modification is done.

3.Genetic Algorithm Applied in Optimal Design of Central Air-Conditioning Water System

3. 1 Mathematical Model of Air-Conditioning Pipe Network Optimization

3.1.1 Objective function

In the optimal design of air-conditioning water system, annual converting cost is regarded as objective function. Annual converting cost includes the initial investment, operating cost and maintenance and amortization expense[4], where:

(1) The overall investment is calculated using equation (1):

$$Cost\_invest = \sum_{i=1}^{n} f(d_i)l_i \qquad (1)$$

where n, d_i, l_i represent the sum of the pipe network branches, the pipe diameter (m) and the length(m) of branch I, respectively. $f(d_i)$ refers to the cost(yuan) of branch I per length. $f(d_i) = a + b \cdot d_i$, a and b denote the regression coefficients.

(2) The annual operating cost includes the power cost of operating water pump, amortization expense and maintenance cost. The power cost of water pump is calculated as follows:

$$Cost\_run = 2.78\times10^{-7}\frac{GH}{\rho\eta_P}\tau\cdot j_d \qquad (2)$$

where 2.78×10^{-7} , G , H , ρ , η_P , τ , j_d represent unit conversion coefficient, water flow(kg/h) , pump heat (Pa), water density(kg/m^3) ,pump efficiency , annual maximum work hours (h)and electricity price(yuan/kWh), respectively.

(3) Annual average amortization expense and maintenance cost as calculated using equation (3):

$$Cost\_\text{depreciation} = \alpha Cost\_invest \qquad (3)$$

where α refers to depreciation rate.

(4) The globle cost of air conditioning pipe network is as follows:

$$Cost = (\alpha + X_t)\text{cos}t\_invest + \text{cos}t\_run \qquad (4)$$

where $Cost$ refers to the annual conversion expense of air conditioning pipe network(yuan/year). X_t represents standard investment effect coefficient.

3.2 Constrained Conditions

(1) Constrained condition of flow

Based on the graph and pipe network theory, the pipe network of the air-conditioning water system can be drawn the network figure which consists of serial branches and nodal points of branches connection. The flow balance equation means that the sum of water flow of all branches connected to a nodal point is zero. The pipe network of n branches and m nodal points has n unknown branches flow. The flow balance equation could be described with formula 5 using incidence matrix [5].

$$\sum_{j=1}^{n} b_{kj}G_j = 0 \qquad k=1,2,\cdots,m\text{-}1 \qquad (5)$$

where k , j, G_j, m , , n , represent node numbering（k =1,2,3⋯,m）, branch numbering（j =1,2,3⋯,n）, branch j flow（kg/h）, the node number, the branch number,., respectively. b_{kj} refer to flow direction function, If node k is correlated to branch j and it is starting point of branch j, b_{kj} is equal to 1; If node k is not correlated to branch j, b_{kj} is equal to 0; If node k is correlated to branch j and it is end point of branch j, b_{kj} is equal to –1.

(2) Constrained condition of pressure

The pressure balance denotes that algebraic sum of the pressure difference in any circuit of pipe network is zero. The pressure balance equation shows as follows

$$\sum_{j=1}^{n} C_{ij}(S_jG_j^{\ 2} - H_{Bj} - H_{Nj}) = 0 \qquad (6)$$

where k, i, S_j, H_{Bj}, H_{Nj} represent independence circuit numbering(i=1,2, ⋯ ,b), pipe resistance number（Pa/(kg/ h)^2）, pump heat in the jth branch（Pa）, potential energy difference of the jth branch, respectively. C_{ij} is a direction function, C_{ij} is equal to 1 if the jth branch belongs to the ith return, and the direction of water flow is uniform with the direction of pipe network circuit ,; C_{ij} is equal to 0 if the jth branch does not belong to the ith return; C_{ij} is equal to –1 if the jth branch belongs to the ith return, and the direction of water flow is non-uniform with the direction of pipe network circuit ,.

(3) Constrained condition of occupants' flow requirements

The Constrained condition represents that computation flow should be bigger than design value,

$$G_j^{'} \geq G_j \qquad (7)$$

(4) Constrained condition of Velocity of pipe is as follows:

$$V_{\min} \leq V \leq V_{\max} \qquad (8)$$

(5) Constrained condition of Pipe diameter is as follows:

$$d_{\min} \leq d \leq d_{\max} \qquad (9)$$

Standard pipe diameters are discrete variables, and they are selected in the limit range. It should regard the discrete pipe diameter as the decision-making variable.

4. GA METHODOLOGY OF PIPE OPTIMIZATION[6,7,8]

4.1 Pipe Diameter Coding

Binary, decimal or integer coding can be selected used in GA coding methods. Considering that standard pipe diameters are discrete variables, integer coding is a preferable mode. Every chromosome' length is equal to the number of the pipe branches. Pipe diameters varying from DN25~DN1000 have 20 standard diameters, each gene is represented by the integer number of 1~20.

4.2 Initial Population Generating

The process of pipe optimization using GA begins with an initial number (population size) called the initial generation, which is defined randomly and regarded as the candidate solution in the integer mode. The population size is determined by the studied cases. population sizes would be increased with the range of variable values. The population is more large, the overall objective is more optimal. It should be noted that the calculation process corresponding to larger population is time-consuming. The population with the number of 20~200 is advisable.

4.3 Hydraulic Computation of Pipe Network

When GA is used in pipe optimal design, hydraulic computation of pipe network should be done. By hydraulic calculation, pressure loss, cycling pump head and flow are obtained. Then, the objective function values would be calculated, and joints flow balance and circuit pressure balance are achieved.

4.4 Fitness Evaluation

Fitness value for each candidates solution is calculated in the following three steps:

1. The integer strings are decoded to values of the design pipe diameter.
2. Hydraulic calculation of water system is conducted to obtain the practical flows of the pipe branches, pump heat and flow.
3. A detailed assessment of annual cost function values is conducted, then the fitness function is as follows:

$$F = C - (COST + k_1 G + k_2 V) \qquad (10)$$

the expression C refers to a large number, $k_1 G$, $k_2 V$ represents penalty items of user flow and velocity, where,

$$k_1 G = k_1 \max(\left|G_j^{'} - G_j\right|) \qquad j = 1,2,\cdots,n \qquad (11)$$

$$k_2 V = k_2 \begin{cases} \max(V_j^{'} - V_j) & V < V_{\min} \quad or \quad V > V_{\max} \\ 0 & V_{\min} \leq V \leq V_{\max} \end{cases} \qquad (12)$$

where k_1, k_2 —penalty factors.

4.5 Selection Operator

Selection operator in GA use tournament method in which three individuals are selected every once. The individual with maximum fitness value is regarded as parent.

4.6 Crossover Operator

Crossover operator is key process in GA. It cannot produce new gene, but the individual fitness values will be raised quickly by recombining better individuals to new ones. By comparison the data, one-point crossover is adopted.

4.7 Mutation Operator

Mutation operator is a process to generate a new individual randomly. In the way, multi-population is warranted. During the process, a random gene position is selected firstly. Next, the corresponding gene is varied randomly within the range of standard pipe sizes. However, unfavorable individuals inevitably occur due to the random process. For the sake of avoiding the disadvantage results, the pipe diameter corresponding to the selected gene is varied according to the manner, in which the pipe diameter is increased or decreased to the adjacent one. In addition, probability of crossover and mutation is generated by self-adapting algorithm[9].

The flow chart of pipe optimization program using GA is shown in Fig.1.

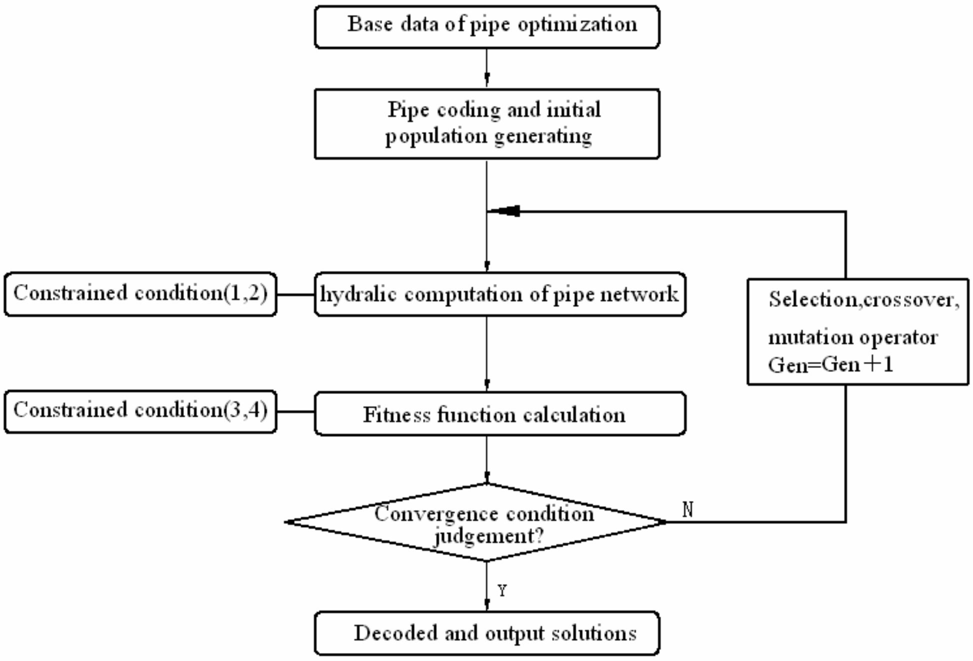

Fig.1. The flow chart of pipe optimization program using GA

5. CASE ANALYSIS

28-story Baoli square is a mixed- usefulness high-rising building with area of 35600 m^2. It was built in Wuxi, jiangsu, China. The lower 3-story is commercial area. Floor 4~15 is for hotel and floor 16~27 is used for office. Central air-conditioning system was installed in the building. Cooling load is 4600kW in summer and the index of cooling load is 130W/ m^2. Heat load is 3600kW in winter and the index of heat load is 100W/ m^2. Cooling source of air-conditioning system is from ice storage units, and heat source is from municipal steam system. Central flow meters, solenoid valves and temperature sensors are installed in return water pipe. The energy consumption of the system is calculated by proportion integration mode. Additionally, equilibrium valves are installed in return water pipe of each circuit[10]. As for hotel, the system adopts the pattern of upward supply and downward return water (as shown in Fig.2). Total of 12 rising pipes transfer cooling and heating loads.

In analyzing the project, the related parameters are as follows: power price(j_d) is 0.60yuan/(kWh); the average density of water (ρ) is 1000 kg/ m^3; pump efficiency(ηp) is 0.7; the operating time(m) is 5760 hours; investment payback period is five years; the depreciation rate(λ) is 6%. Equivalent roughness of pipe wall is 0.2 mm; local resistance head cost is 30 percent of the friction resistance head cost.

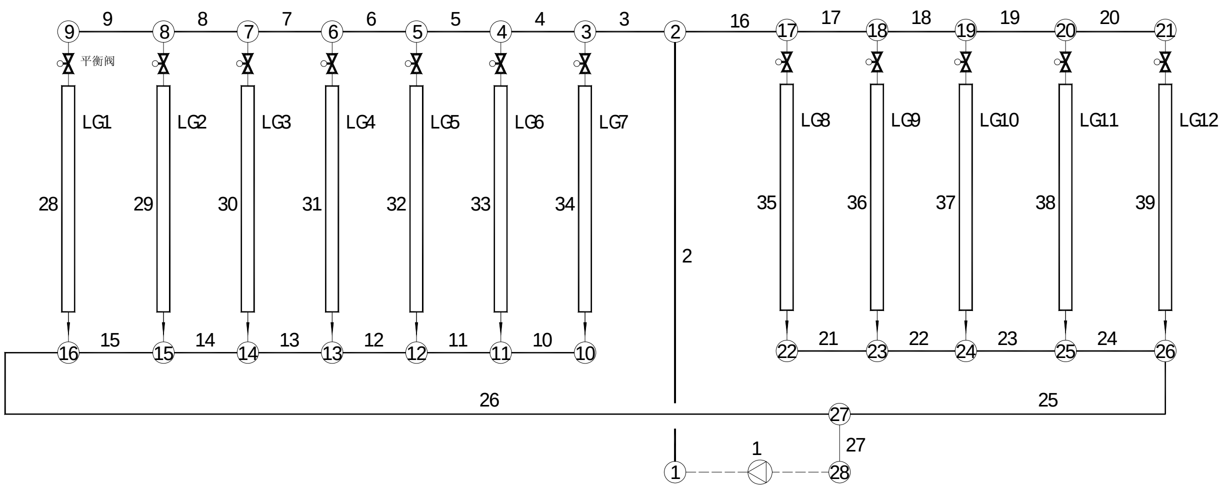

Fig. 2 Network graph of air-conditioning water system of the hotel area of the 4th building

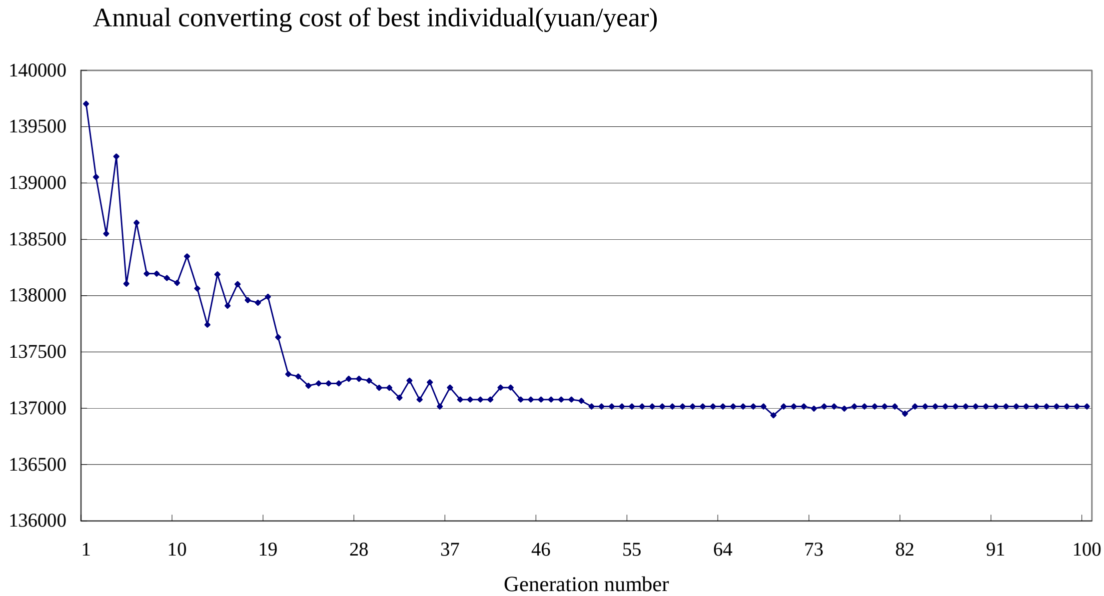

Fig.3 Evolution of annual converting cost of best individual

The cost of pipe network is calculated by the estimation indices provided in references [11]. The obtained regression coefficients are: a =67.54yuan/m; b =4708.65yuan/m^2.

The GA parameters used in solving this problem are a population size of 60, maximum generations of 100. Fig.3 shows the evolution of annual converting cost best individual with the generation.

Table 1 demonstrates the results from recommended velocity method and GA optimal design method. Annual converting cost from recommended velocity method is 139613 yuan, whereas, the cost of best individual from GA method is 136936.2 yuan, indicating 2677yuan has been saved.

6. CONCLUSION

GA has the advantage of tackling this problem of discrete variable, non linear programming, multi-constraint. The method can carry out multi-path and search optimization. The calculation process is simple and the results is reliable. The analysis of the practical project demonstrates that GA is effective to seek optimal pipe size of air-conditioning water system. It is concluded that genetic algorithm provides better optimal solutions for the design of air-conditioning water system.

Tab. 1 Results from the recommended velocity method and GA optimal design method

Branch	Starting point	End point	Pipe length (m)	Velocity method design solution				GA optimal design solution				
				Pipe radius (mm)	Flow (m^3/h)	Resistence factors ($Pa/(m^3/h)^2$)	Velocity *(m/s)*	Pipe radium (mm)	Flow (m^3/h)	Resistence factors ($Pa/(m^3/h)^2$)	Pressure (*Pa*)	Velocity *(m/s)*
1	28	1	20	250	314.25	0.8	1.66	250	337.16	0.8256	93849.61	1.7785
2	1	2	61.2	250	314.25	0.0783	1.66	250	337.16	0.0783	8899.945	1.7785
3	2	3	1	200	139.58	0.0041	1.15	200	147.9	0.0041	90.7574	1.2214
4	3	4	8.25	200	117.3	0.0342	0.97	150	125.11	0.1857	2906.472	1.9676
5	4	5	1.5	200	95.01	0.0062	0.78	150	101.88	0.0338	350.4405	1.6023
6	5	6	4.5	150	86.51	0.1013	1.36	150	92.47	0.1013	865.9853	1.4543
7	6	7	4.5	125	53.08	0.2638	1.20	100	55.43	0.8511	2615.261	1.9615
8	7	8	1.5	125	44.57	0.0879	1.01	100	46.02	0.2837	600.7542	1.6283
9	8	9	8.25	80	22.29	4.423	1.17	65	22.79	10.9468	5684.297	1.6937
10	10	11	8.25	80	22.29	4.423	1.17	65	22.79	10.9468	5684.297	1.6937
11	11	12	1.5	125	44.57	0.0879	1.01	100	46.02	0.2837	600.7541	1.6283
12	12	13	4.5	125	53.08	0.2638	1.20	100	55.43	0.8511	2615.262	1.9615
13	13	14	4.5	150	86.51	0.1013	1.36	150	92.47	0.1013	865.9853	1.4543
14	14	15	1.5	200	95.01	0.0062	0.78	150	101.88	0.0338	350.4406	1.6023
15	15	16	8.25	200	117.3	0.0342	0.97	150	125.11	0.1857	2906.47	1.9676

16	2	17	7.2	200	174.67	0.0299	1.44	200	189.26	0.0299	1070.019	1.5629
17	17	18	1	200	152.38	0.0041	1.26	200	165.02	0.0041	112.9814	1.3628
18	18	19	5.25	150	121.86	0.1182	1.92	200	131.55	0.0218	376.9729	1.0864
19	19	20	4.5	150	99.58	0.1013	1.57	150	107.18	0.1013	1163.561	1.6857
20	20	21	1.8	80	22.29	0.965	1.17	65	24.28	2.3884	1408.019	1.8046
21	22	23	1	80	22.29	0.5361	1.17	80	24.24	0.5361	315.0493	1.2757
22	23	24	5.25	125	52.8	0.3077	1.20	125	57.71	0.3077	1024.72	1.3068
23	24	25	4.5	150	75.09	0.1013	1.18	125	82.07	0.2638	1776.809	1.8587
24	25	26	1.8	200	152.38	0.0075	1.26	200	164.98	0.0075	203.2707	1.3624
25	26	27	1	200	174.67	0.0041	1.44	250	189.26	0.0013	45.8226	0.9984
26	16	27	7.5	200	139.58	0.0311	1.15	200	147.9	0.0311	680.6806	1.2214
27	27	28	4.5	250	314.25	0.0058	1.66	250	337.16	0.0058	654.4077	1.7785
28	9	16	3	100	22.29	132.9	0.79	65	22.79	136.8806	71077.69	1.6937
29	8	15	3	100	22.29	132.9	0.79	65	23.23	136.8806	73855.52	1.7264
30	7	14	3	65	8.5	774.7	0.63	40	9.42	835.9062	74105.83	1.982
31	6	13	3	100	33.43	53.69	1.18	80	37.04	55.2984	75855.11	1.9491
32	5	12	3	65	8.5	774.7	0.63	40	9.42	835.9062	74105.83	1.982
33	4	11	3	80	22.29	132.9	1.17	65	23.23	136.8806	73855.52	1.7264
34	3	10	3	80	22.29	132.9	1.17	65	22.79	136.8806	71077.69	1.6937
35	17	22	3	80	22.29	132.9	1.17	65	24.24	136.8806	80436.63	1.8017
36	18	23	3	80	30.51	70.4	1.61	80	33.46	72.0084	80638.7	1.7611
37	19	24	3	80	22.29	132.9	1.17	65	24.37	136.8806	81286.45	1.8112
38	20	25	3	125	77.29	11.74	1.75	125	82.9	11.9158	81899.7	1.8775
39	21	26	3	80	22.29	132.9	1.17	65	24.28	136.8806	80694.95	1.8046

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